Human/Robotic Exploration of the Solar System

Request for Information to the Universities Space Research Association

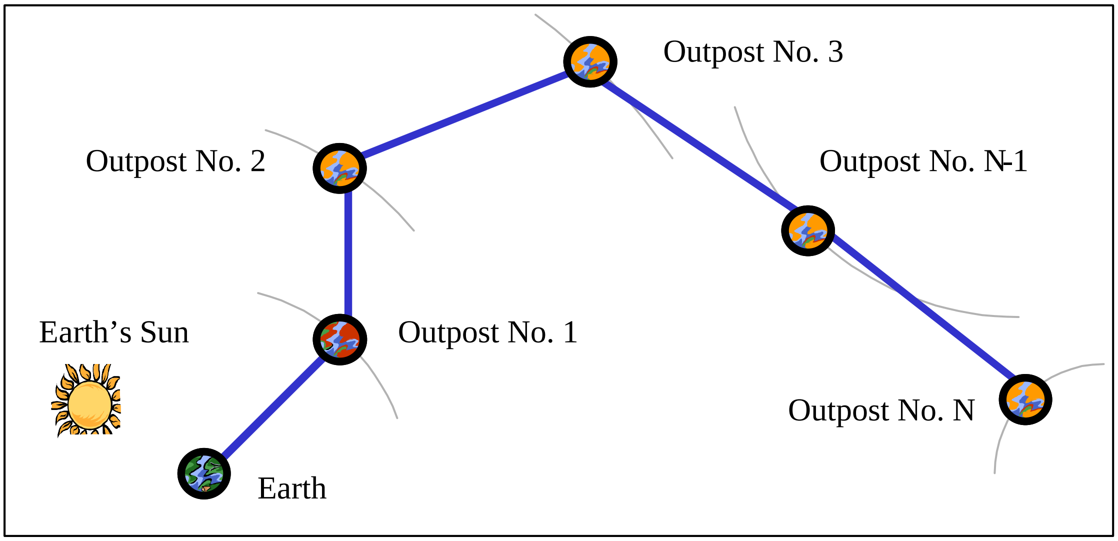
Wendell H. Chun
Lockheed Martin Space Systems Company
P.O. Box 179
Denver, CO 80201

Robots or unmanned vehicles are ideal for precursor missions. They can be more robust than humans, and can compensate for the frailties of the human body, e.g. resisting high gravitational forces, etc. Following Moore's Law on computer processing evolution, these robots will eventually become autonomous sometime in the next 10 - 40 year horizon. Autonomous operations include adapting to its environment, making decisions, and reasoning about its actions. The idea of a perfect robot for exploration of the solar system has the following attributes:

- Having long life and is self-sustaining,
- Having the capability to protect and safe itself,
- Is adaptable to a variety of terrains and environmental conditions,
- Self-repairing, and
- Re-directable by human counterparts to achieve a common goal.

If future propulsion technology cannot allow man to travel directly to his solar system destination in a direct and timely manner, stopping points will be required. These stopping points will function as waypoints or outposts. To reach any far destination, future space explorers will have to rely on these outposts. They can offer fuel, shelter, supplies, and possibly human food. Eventually, a network of outposts will be required for NASA to grow out of our own solar system. Earth will be the center of this architecture made up of many outposts that are expanding outwards over time.

While humans are currently limited in space travel, why not send robots to build these outposts while we solve the problems of human flight? Even if we don't get to them in the next 40 years, someday we will require the use of these outposts. The robot does not have to look like a man[1], but must be a smart machine. It is a matter of time before a robot can be autonomous, but it may take even longer to become intelligent. Robot technology will evolve from automata to autonomous to intelligent over time. If this robot could survive for a nominal 40 years or one hundred years and stay productive the entire time, we have obtained a robot that has long-life and is somehow self-sustaining. As an analogy, many mechanical engineering components have not changed drastically in the past fifty years, e.g. screw fastener. It must protect itself from the environment (and the environment will vary from locale to locale) and other unforeseen hazards. The missions could get dangerous for the robots, and some robots are expected to be lost or rendered inoperable for a variety of reasons. However, can we leave them alone for a long period of time and have them be productive. Being productive is building structure or roads for as long as it takes for humans to someday visit this outpost.



Earth's Outpost Architecture for Exploration of the Solar System

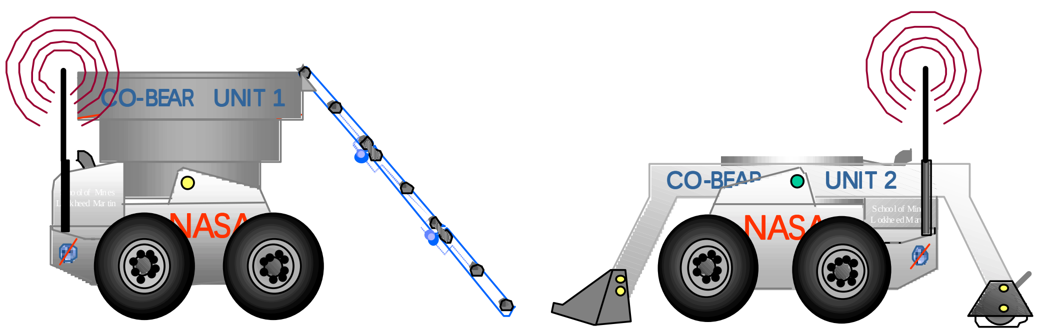
A similar scenario occurs when an unknown Spanish explorer of the 16th century blazed a path through an overgrown jungle, only to find a city of gold. When humans finally get to these outposts, they will be amazed by what they will find. The infrastructure will not be blueprint McDonalds Hamburger Restaurants that all look alike, but functionally each outpost would offer the same basic items as mentioned earlier. Summarizing, the major tasks for the robots include survival, productivity, and the ability to work side-by-side with humans.

A) Advanced Revolutionary System Concept

Robot teams are launched to the first outpost, probably to the moon or Mars. This team will consist of three or four robots that could each search, dig, push, carry, lift, etc. Each robot has a primary specific function that complements one another. The goal is to have a projected life for these robots of 100 years, maintenance-free in order to be productive. Sensors, processing, electronics, and software become relatively cheap in the future, thus proliferating robot exploration. They will adapt to their new environment and must first insure their survival. As a contingency, there is always a spare robot on each team. Like other multi-functional teams, the robots are cross-trained to accomplish multiple jobs and functions. Having some assurance of survival, the robots can work continuously without jeopardizing their own health. First comes a robot shelter, which may or may not have to double later as a human shelter. The robots must tend to their own needs first. They work in teams, starting with surveying and mapping of the landing site. Having mapped their local area, they have two major goals: 1) be productive, and 2) expand their local map. This is in essence a robot colony. Being productive is developing the infrastructure for humans to one-day use and possibly occupy. Again, this could be shelter, agriculture, propellant production, oxygen production, possible tunnels connecting structures, walls and barriers, etc.

Robot Colony

The robots themselves are autonomous and cooperative. Two robots could excavate and transports regolith, which is a paradigm shift from current thinking on how to carry out complex tasks with robots. A robotic team offers the possibility of spatially distributed sensing and acting, similar in many ways to distributed computing. For example, one heterogeneous vehicle could till and collect soil resources, and the other could store and later transport the resources to the outpost. When one vehicle is transporting the regolith, the remaining vehicle will aid in navigation by becoming a beacon (artificial landmark) with the outpost such that the other vehicle could triangulate to.



Example of Two Robots from a Possible Team of Four

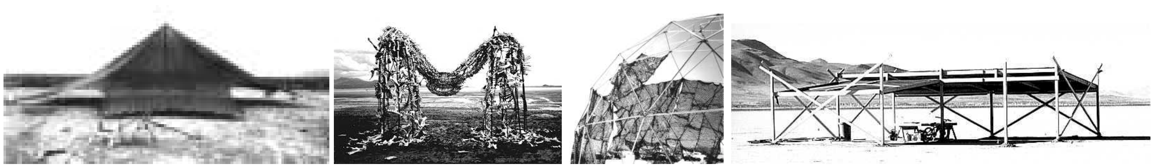
Multiple robots that are cooperative offer greater flexibility and reliability in a mission. The complexity of searching, finding, mining, and transporting may require a team of (again, possibly heterogeneous) robots to work together to accomplish its missions that no individual robot could accomplish alone (based maybe on packaging constraints) and in a timely manner. Some fundamental, cooperative robotic applications or behaviors include flocking, dispersion, aggregation, and following, as well as individual obstacle avoidance and go-to-goal behaviors. These routines address task decomposition, task allocation, achieving coherence amidst distribution of control, resolution of subgoal conflicts, reasoning about the activities of other machines, and inter-robot communication. These basic building blocks can now be used for more complex, real-world applications, such as a generalized search for the in-situ resource problem, and for the automatic design of cooperative robot behaviors for harvesting, construction, collection, and storage.

Robot colonies bring up new issues such as robot-to-robot communications, spatial task distribution, differences between heterogeneous and homogeneous societies, and interference management that needs addressing to foster coordination and productivity. To address these issues, each robot has to be equipped with sensors (both internal and external), adequate processing for implementing intelligence, actuators or effectors, and an inter-robot communication system such as radio ethernet (however not for Mars). The most difficult sensor will be the one to locate the correct soil to harvest for in-situ propellant production. The software on each robot is made up of many little programs, or behaviors. Each behavior monitors a set of the robot's sensors and outputs an appropriate action command based on a hierarchy, with the more important behaviors overriding the outputs of less important behaviors (i.e. Subsumption[2]). In order to accomplish its mission, it will have to switch back-and-forth between several hierarchies of behaviors depending on the situation.

Once a suitable spot is located for collecting soil, the two robots must be better coordinated to achieve their common objective, e.g. transfer of resources. The architecture for the colony will depend upon whether it is centralized or decentralized, and whether it is hierarchical or distributed. There will be several types of interactions based on the environment, external sensing, and communications. Resource conflicts between the robots, the origin of cooperation, learning, and geometric problems in the real world will have to be addressed.

<u>Human/Robot Collaboration</u>

The robots could be working in isolation for five to fifty to one hundred years before they receive their first visitor. When the first humans arrive at the outpost, these explorers will have a mixed emotion of excitement and disappointment when viewing the creation of the robots for the first time.



What will this 10-40 year outpost look like when humans arrive?

In all probability, there will be some re-work to make the outpost more suitable to human habitation. The longer the humans plan or are forced to stay, the greater the amount of re-work that has to be done to what has already been built. The issue here becomes how does the human and robot work together. There are various working strategies being investigated today, such as using Cobots[3], a class of hybrid human-controlled/computer-controlled material handling robots. Cobots are assist devices for workers in an automobile factory where the robot is separated from the human by software-defined *virtual guiding surfaces*. Other related research includes examples such as the CMU Social Robots Project[4], the CMU Interactive Robot Programming[5] and the University of British Columbia's Constraint-based Visual Robotic Systems Project[6]. A key issue is can a robot converse with a human and vice versa if their internal architectures are noticeably different. And what is this medium for communication, and is it adequate to transfer the intent of each other sufficiently to collaborate?

B) Identification of Required Technologies to Enable these Capabilities

There are several enabling technologies in this concept: 1) extremely long life robots, 2) robot autonomy, 3) survivability and self-repair, 4) cooperative robots to do productive work in a colony, and 5) human-robot interaction.

Long-Life Robots

Most everyone values well-built objects that last a longtime, e.g. good furniture, classic automobiles, etc. As another example, the perpetual-motion-machine is another sought-after prize of engineers because of its difficulty, but with a promise to provide unprecedented value. A robot that had the capability to operate forever with minimal or no maintenance would be beneficial for space exploration. Taking the appropriate precautions, a nuclear-powered robot could take advantage of the long half-life of its source material. This source of power is constant over a long period of time. However, it might not produce enough power for some peak tasks, and would have to leverage a supplemental source of power such as wind, solar, or thermal, along with energy storage. In order to achieve the desired long life, the robot would need periodic self-maintenance.

Robot Autonomy

Mathematicians like Kurt Gödel and Alan Turing revealed to us what machines can be made to do, and later in the 1940s when Warren McCulloch and Walter Pitts began to show how machines could be made to see, reason, and remember. Stimulated by the invention of the modern computer in the 1950s, new ideas emerged on how machines could do what only the human mind had previously done with "intelligence". Early artificial intelligence techniques tended to exploit knowledge representation with mediocre success. However, limitations from the processor were soon changed so that many of these early techniques could be re-used with much greater success. The tens of MIPS of the 1980s will evolve to processing 100,000,000 MIPS in the 2050 timeframe if processing capability continues to follow Gordon Moore's Law. Instead of having an automaton robot following rules, autonomous robots will be evaluating alternatives and making decisions. Some of these decisions will be based on rules while other decisions will be extracted from cognition. It was first assumed that intelligence requires knowledge, and artificial intelligence can exploit knowledge representations that are characterized by some undesirable properties: voluminous data, hard to characterize scenes, and constantly changing environments. Autonomous robot systems vary in robustness from a mere 30,000 lines of code in JPL's *Intelligent Agent* to a staggering 1.5 million lines of code on Lockheed Martin's UGV Demo II program[7]. The UGV Demo II vehicles are HMMWVs that perform an unmanned reconnaissance and surveillance mission for the army. Fifty years from now, autonomous robots will be able to learn, remember, and reason about itself and its environment.

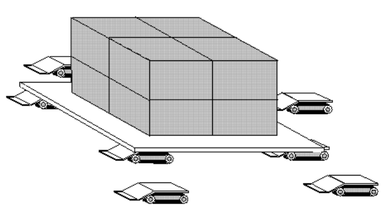
UGV Demo II Robots

Survivability and Repair

To survive in harsh environments, the robot must able to control its internal temperature. Sometime it is rejecting heat and at some other locale, it might be taking in heat. There must be automatic temperature-control, radiation control, i.e. environmental control. Just like a human, when the robot runs low on energy, it must be able to rest and recuperate. During the course of being productive, the robot might fall into harms way where it could be damaged or even disabled. Thus, somehow it must repair itself[8]. The robot must first diagnose the problem, and eventually determine a course of action to correct the situation.

Cooperative Robots

Cooperating autonomous robots are characterized as intelligent systems that integrate perception, reasoning, and action to perform cooperative tasks under circumstances that are insufficiently known in advance, and dynamically changing during task execution. To test cooperative methodologies, the Cooperating Autonomous Robots[9] group at Oak Ridge National Lab (ORNL) have demonstrated four indoor robots equipped with a variety of sensors, including odometric, tactile, sonar, infrared, 2D laser, vision, and compass sensors, as well as an indoor laser-based 2D global positioning system for localization. The robots are equipped with a radio Ethernet system in the lab that allows inter-robot communication, as well as communication to host development workstations. These robots are used to understand the issues associated with robots functioning and working together.

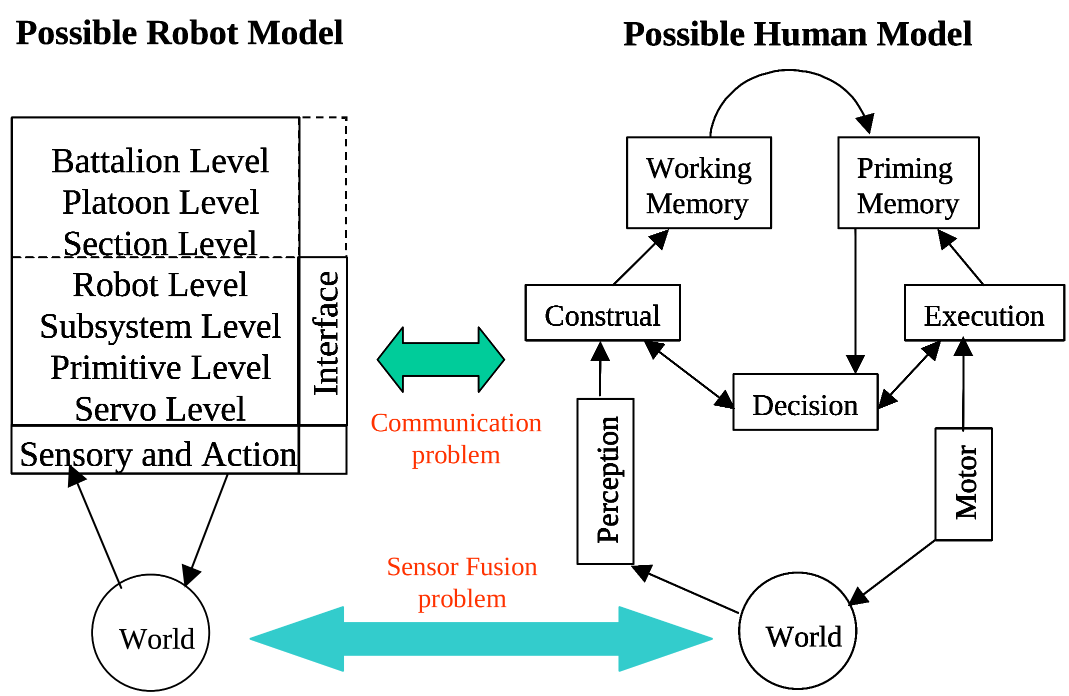


Virginia Tech's Army Ant Robots

The complexity of many real-world robotic applications requires teams of robots to work together to accomplish missions that no individual robot could accomplish alone. The goal of cooperative robots is to develop original, generally applicable methodologies facilitating the fault tolerant cooperation of autonomous mobile robots. The research issues that ORNL have successfully addressed were to develop a cooperative robotics software library that include task decomposition, task allocation, achieving coherence amidst distribution of control, resolution of subgoal conflicts, reasoning about the activities of other agents, and inter-robot communication. These basic building blocks are now being used for complex cooperative team applications, such as generalized distributed spatial coverage problems, and for the automatic design of cooperative robot behaviors for selected applications.

Human/Robot Interaction

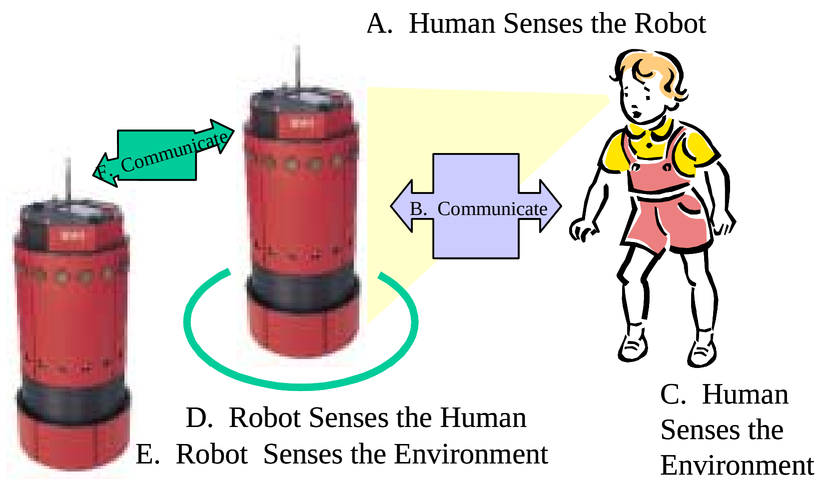
Key to robot and human collaboration is communications between the two. The robot may have a hierarchical architecture or a distributed architecture, e.g. utilizing a behavior-based approach, while the human is yet to be defined, but demonstrates characteristics of both. The human brain is neither digital nor analog. The interaction issue becomes how does the human think and communicate with the robot? Current communication approaches include Ethernet communication or serial communication over an RF link, utilizing voice commands and/or human interactive dialogue. There is another approach that we are suggesting such that the verbal commands of the human are at a high level of abstraction and is automatically decomposed to lower, working commands that are communicated over multiple parallel links that are addressed to the appropriate levels in a robot system architecture similar to the way internet TCP/IP protocol standards work. Similarly, the various levels of action of the robot is communicated over this same two-way link and modulated to a higher level of abstraction to which the human could understand. The result is a human that communicates to a robot using voice over a wearable computer that links to the robot over a parallel communication transmitter and receiver. The robot must also have this same communication transmitter and receiver equipment. Together this device can be thought of as a robot translator/communicator for the human. This will enable humans and robots to work together, side by side.



How do the Human and Robot Communicate together with Dissimilar Architectures?

C) Evaluation of the Evolution of the Relative Roles of Humans and Machines to Implement these Concepts

In partnership with the Colorado School of Mines, Lockheed Martin is investigating the communications between human and robot, as well as between robot and robot. In order for the human to work in conjunction with a robot, it must first understand the robot's actions and be able to communicate with the robot at the same time. In addition to sensing the robot, the human requires an understanding of the environment the human is in, which includes the robot. Reciprocally, the robot does the same thing. It senses the human, its environment, and can postulate what the human will do next. This understanding is tightly coupled. Together with direct communication using the aforementioned robot translator/communicator, experiments testing the collaborative nature of robot and human can be achieved. A common goal is to bind the actions of the human and the robot such that a safe working arrangement could be arrived at. As this level of understanding matures, the complexity of the environment could be increased by taking the robot and human outdoors into a more exploration-type of environment (unstructured and constantly changing). An interesting artifact will be to correlate the human's sense of the environment including the robot and the robot's sense of the environment including human. Differences between both models of the environment are central to the sensor fusion problem depicted in the previous diagram.



Colorado School of Mines' Proposed Robot Interaction Lab

The second part of this proposed experiment is to understand the robot-to-robot communication problem based on a similar two-way link that passes messages in parallel. This will be accomplished by adding a second mobile robot that is also autonomous. Having two commercial indoor mobile robots communicating under full synchronization will be a stepping-stone to having two outdoor mobile robots working together as shown earlier (excavation and transport robots). The content of these messages would be different from a robot-human interaction. This is the early foundation of a robot colony. Given a long lifetime for the robots, the opportunity for robots to be productive would be interesting. As robot autonomy and learning techniques improve, they can be inserted onto the robot over time such that these autonomous robots could evolve and become more capable. This ability to work with humans will also enhance the productivity of the robots when not being supervised. They will be in a learning mode.

D) Indication of the Science that would be enabled by these Capabilities

Robots that could operate autonomously and for extremely long periods of time would be very beneficial to building infrastructure for human exploration of the solar system. This technology could also be used on Earth in the most hazardous of environments. As autonomous robot technology improves, so can these robots improve. They could someday build a city underwater or in the desert or on frozen tundra. What may be a first step towards productivity, these robots could mature quicker by working side-by-side with humans and capture the intent of humans by learning in real-time. Time will be on the side of the robot colony to meticulously create something useful. This would be an enabling technology to allow humans to use an architecture of outposts to travel to distant locations in the universe. Over time, this network could become the highway to the stars.

The robot translator/communicator is needed to enable a human to communicate effectively with the robot and vice versa. This device will be different from the way robots communicate with other robots. The translator exists in the form of a wearable computer on a human and a like-processor inside of the robot. The parallel communication system is a new device that could be made up of a radio frequency system of various bands with specific addresses to connect to selected levels of the robot. This implies information is passed up and down in a hierarchy, as well as left and right from human to robot and vice versa.

It is possible to speed up the number of outposts in this architecture if robots could somehow build more robots. And if these robots could ever launch themselves to another planet and repeat the process, colonization of the solar system could begin, even if humans are never to see every outpost. However, robots producing robots and launch vehicles would be another major paradigm-shift. Our first step is to make robots autonomous and eventually productive. The research community is working to this means, but have a long way to go. Subsequently, a human could direct or manage a robot helper using the translator/communicator. Our first robot could communicate with other robots such that cooperative robot teams could build the first walls and shelters. Eventually, walls and shelters may lead to outposts that are like cities.

E) References

1. Issac Asimov, *I, Robot*, Bantam Books © 1950.
2. Rodney Brooks, *Cambrian Intelligence: The Early History of the New Ai*, MIT Press, © 1999.
3. Wannasuphoprasit, Gillespie, Brent, Colgate, Peshkin, “Cobot Control”, IEEE International Conference on Robotics and Automation, Albuquerque, Vo. 4, pp. 3571-3576.
4. Nakauchi and Simmons, “A Social Robot that Stands in Line”, Proceedings of the Conference on Intelligent Robots and Systems (IROS), Takamatsu, Japan, October 2000.
5. Iba, Vande Weghe, Paredis, and Khosla, "An Architecture for Gesture Based Control of Mobile Robots," Proceedings of the IEEE/RSJ

International Conference on Intelligent Robots and Systems (IROS'99), October 1999.

6. James Little, “Robot Partners: Collaborative Perceptual Robotic Systems”, First International Workshop on Cooperative Distributed Vision, Kyoto, Japan, Oct. 17-18, 1997.
7. Munkeby, S., Shoemaker, C., Chun, W. "Unmanned Ground Vehicle Demo II Program", 1994 IEEE National Telesystems Conference, San Diego, CA, May 1994.
8. Kurokawa, Murata, Yoshida, Tomita, and Kokaji, A Three-Dimensional Self-Reconfigurable System, Advanced Robotics, 13-6, pp.591-602, 2000.
9. Lynne Parker, “ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation”, IEEE Transactions on Robotics and Automation, 14 (2), 1998.

F) Synopsis of Lockheed Martin RFI

- Network of Robotic Outposts radiating from Earth
- Long-Life and sustaining robots that last a hundred years
- Cooperative and Autonomous Robots
- Adaptable to its environments and self-repair capability
- Robots building infrastructure over long periods of time
- Robot-to-Robot Communication
- Human-to-Robot Communication translator/communicator
- Colorado School of Mines’ Robot Interaction Lab
- Robots building robots and launch capability